

Resonant Photonic States in Coupled Heterostructure Photonic Crystal Waveguides

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Abstract In this paper, we study the photonic resonance states and transmission spectra of coupled waveguides made from heterostructure photonic crystals. We consider photonic crystal waveguides made from three photonic crystals A, B and C, where the waveguide heterostructure is denoted as B/A/C/A/B. Due to the band structure engineering, light is confined within crystal A, which thus act as waveguides. Here, photonic crystal C is taken as a nonlinear photonic crystal, which has a band gap that may be modified by applying a pump laser. We have found that the number of bound states within the waveguides depends on the width and well depth of photonic crystal A. It has also been found that when both waveguides are far away from each other, the energies of bound photons in each of the waveguides are degenerate. However, when they are brought close to each other, the degeneracy of the bound states is removed due to the coupling between them, which causes these states to split into pairs. We have also investigated the effect of the pump field on photonic crystal C. We have shown that by applying a pump field, the system may be switched between a double waveguide to a single waveguide, which effectively turns on or off the coupling between degenerate states. This reveals interesting results that can be applied to develop new types of nanophotonic devices such as nano-switches and nano-transistors.

Keywords Photonic crystal heterostructures · Nonlinear photonic crystals · Photonic crystal waveguides · Nanophotonics · Resonant tunneling · Coupled waveguides

Introduction

There has been a great deal of interest in photonic crystals [1, 2] due to their ability to manipulate the propagation of light in the same way that semiconductor materials are able to control the propagation of electrons. Photonic crystals are materials with a dielectric constant that varies periodically in one, two or three spatial dimensions, due to which a photonic band gap forms in the structure's photonic dispersion relation. Significant effort has been devoted to the development of new photonic devices made from photonic crystals. Two promising classes of these materials are photonic crystal heterostructures [3] and nonlinear photonic crystals [4–14].

Photonic crystal heterostructures are formed by joining two or more photonic crystals into a single structure, which gives the heterostructure a more complex band structure than that of a raw photonic crystal [3]. Photonic crystal heterostructures have been successfully used to develop devices such as high-quality resonant cavities [15], low-loss waveguides [16] and high-efficiency add-drop filters [17]. Nonlinear photonic crystals possess a PBG that can be shifted, which makes these materials ideal for developing optical switching devices. Recently, optical switching mechanisms due to nonlinear Kerr effects in photonic crystals have been studied both theoretically [4–9] and experimentally [10–14].

Here, we study the photonic resonance states and transmission spectra in coupled waveguides made from

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heterostructure photonic crystals. Waveguides made by embedding a high refractive index material into a low index material have been widely studied [18]. Some work has also been done on photonic crystal waveguides formed by doping a dielectric material into a photonic crystal. For example, McGurn [19] and Sinha [20] have studied co-directional coupling between two photonic crystal waveguides. Faraon et al. [21] have studied theoretically and experimentally the coupling between photonic crystal waveguides.

In this paper, we consider two linear photonic crystals A and B and a nonlinear photonic crystal C and arrange them as B/A/C/A/B to form the waveguide heterostructure. Crystal parameters for A, B and C are chosen so that the upper band edge of crystal A lies within the band gaps of crystals B and C. Due to this band structure engineering, light is confined within crystal A, which thus act as waveguides. In the confinement direction of the waveguide, photons will occupy discrete quantized states within photonic crystal A, which appear as photonic quantum wells (PQWs). This so-called photonic confinement effect has been demonstrated both theoretically [22–24] and experimentally [25, 26] for various types of PQW systems, analogous to the electronic confinement effect that occurs in semiconductor quantum wells. It has been shown that the phenomenon of resonant tunneling will occur for a PQW with sufficiently thin photonic barriers, whereby an incident photon possessing an energy matching a resonant state of the PQW will undergo perfect transmission through both barriers [22, 23]. Because of this, resonant states appear as sharp peaks approaching unity in the transmission spectrum of a PQW [22–26].

Using the transfer matrix method [22, 24, 27], we have determined the energies of bound photons within the coupled waveguides and calculated the transmission coefficient of the system in the direction of photon confinement. We have found that the number of bound states within the waveguides depends on the width and the well depth of the photonic wells. It has also been found that when both waveguides are far away from each other (or equivalently, the width of photonic crystal C is large), the energies of bound photons within the waveguides are degenerate. However, when the waveguides are brought close to each other, the degeneracy of the bound states is removed due to the coupling between them, which causes these states to split into symmetric and anti-symmetric pairs. We have also investigated the effect of the nonlinearity of photonic crystal C. By applying a pump laser, the photonic band gap of crystal C changes due to the Kerr effect [8]. This change in band structure effectively modifies the energy barrier separating the waveguides, which in turn changes the splitting energy of the coupler. In other words, the energies of the couplers can be switched on and off by applying the

pump laser. This reveals interesting results that can be applied to develop new types of nanophotonic devices such as nano-switches and nano-transistors [4–14].

Theory

We consider three photonic crystals A, B and C, where each is composed of dielectric spheres embedded in a dielectric background material. Dispersion relations for these crystals were obtained using the isotropic band structure model proposed by John and Wang in [28], which has been widely used in the literature of photonic crystals to study their optical properties [8, 28, 29]. For a photonic crystal described by this model, it is considered that all electromagnetic waves propagating within the crystal encounter the same periodically varying dielectric constant, regardless of their polarization or propagation direction. Due to this simplifying assumption, light propagation within this photonic crystal can be described by a scalar wave equation (1-D Maxwell wave equation) for the electric field. By solving the scalar wave equation, we obtain the dispersion relation for photonic crystal i (i.e. $i = A, B$ or C) as

$$\cos(k_i L_i) = \frac{(n_{s,i} + n_{b,i})^2}{4n_{s,i}n_{b,i}} \cos\left[\frac{\varepsilon_k(2n_{s,i}a_i + n_{b,i}b_i)}{\hbar c}\right] - \frac{(n_{s,i} - n_{b,i})^2}{4n_{s,i}n_{b,i}} \cos\left[\frac{\varepsilon_k(2n_{s,i}a_i - n_{b,i}b_i)}{\hbar c}\right] \quad (1)$$

In Eq. (1), k_i is the Bloch wave vector, L_i is the lattice constant, $n_{s,i}$ and $n_{b,i}$ are the indices of refraction of the spheres and background materials, respectively, a_i and b_i are the radius of the spheres and the distance between the spheres, respectively, and ε_k is the photon energy. Although the isotropic band structure model employed here is an idealization, it leads to qualitatively correct physics and has been shown to exhibit many features of observed and simulated band structures for 3-D photonic crystals [28, 29].

The double waveguide heterostructure is formed by arranging photonic crystals A, B and C in the sequence B/A/C/A/B. We consider that the waveguide is symmetric in the direction of photon confinement, such that opposite layers of photonic wells and barriers have equal thicknesses that are given as d_A , d_B and d_C . It is considered here that the spheres in photonic crystal C consist of a nonlinear dielectric material, such that their refractive index in the presence of an intense pump field is given as [8, 30]

$$n_{s,C} = n_0 + n_{NL}I \quad (2)$$

where n_{NL} is a function of the third-order susceptibility, which can be positive or negative depending on the

dielectric material being used, and I is the intensity of the pump field laser. When the pump laser is applied, the band gap of photonic crystal C will be shifted due to the Kerr nonlinearity (Fig. 1).

Here, we choose crystal parameters such that the upper band edges of photonic crystals B and C are almost equal, and the upper band edge of photonic crystal A is below that of B and C, but not so far as to form a deep photonic well. This is done to ensure that the photonic wells formed within crystal A are shallow enough so that the shift in the band gap of crystal C will be great enough to eliminate the central photonic barrier. Thus, we can switch the system between a double waveguide and single, wider waveguide by applying a pump field.

It is considered that light in the form of transverse electric waves is incident upon the waveguide heterostructure in the direction of photon confinement. The transmission coefficient of the heterostructure is calculated for the confinement direction using the transfer matrix method [27], which matches the electric field and its first derivative at the interfaces between adjacent photonic crystal layers in order to relate the incident and reflected amplitudes in each layer via transfer matrix equation. The transfer matrix method is ideal for our simulations, because we are considering isotropic photonic crystals, and we are only concerned with light propagation along the direction

of photon confinement. In principle, a photonic waveguide does not allow transmission through the outer photonic barriers, but here we allow for transmission to occur by choosing sufficiently thin outer photonic barriers that permit photonic tunneling to occur. We do this in order to study the resonant tunneling effect that occurs as a result, whereby the behavior of the bound photonic states in the waveguide can be studied from its transmission spectra. The energies of the bound states are not affected by the thickness of the outer photonic barriers, so this has no effect on energies of the bound states within the waveguides or their coupling strength. Using the dispersion relation given in Eq. (1), the transmission coefficient was obtained as a function of the incident photon energy and was plotted over the range of energies between the upper band edges of photonic crystals A and B in order to find the resonant states of the system. The transmission spectra were studied for instances when the pump field is on or off in order to observe the switching effect produced.

Results

We consider a coupled heterostructure photonic crystal waveguide consisting of crystals A, B and C arranged as B/A/C/A/B. For these crystals, their specific 3-D lattice structures are not be specified, as the isotropic band structure model employed here is independent of the type of lattice considered. Photonic crystals A, B and C each have a dielectric background material consisting of titania (TiO_2), such that $n_{s,A} = n_{s,B} = n_{s,C} = 2.5$ [30, 31]. The spheres in crystals A and B are taken to be filled with air $n_{b,A} = n_{b,B} = 1.00$, whereas the dielectric spheres in crystal C are made of polystyrene, with $n_o = 1.59$ and $n_{nL} = 1.14 \times 10^{-12} \text{ cm}^2/\text{W}$ [9]. We choose polystyrene as our nonlinear dielectric material due to its strong and fast Kerr nonlinear optical response [9, 14]. Since the third-order nonlinear susceptibility of titania is on the order of $10^{-15} \text{ cm}^2/\text{W}$ [30], photonic crystals A and B are considered to be linear in our simulations. The radii of the spheres in all three photonic crystals were taken as $a_A = a_B = a_C = 125 \text{ nm}$, and the lattice constants for each crystal were taken as $L_A = 520 \text{ nm}$, $L_B = 510 \text{ nm}$ and $L_C = 435 \text{ nm}$. The upper photonic band edges of photonic crystals A and B were calculated from Eq. (1) as 0.79273 eV and 0.81830 eV, respectively. When the pump field is off, the upper photonic band edge of photonic crystal C is found to be 0.82349 eV. Transmission spectra of the heterostructure are plotted between the upper band edges of photonic crystals A and B in order to study the resonant photonic states in the waveguide heterostructure.

In Fig. 2, we study the effect of the coupling between the waveguides by varying the thickness of the central

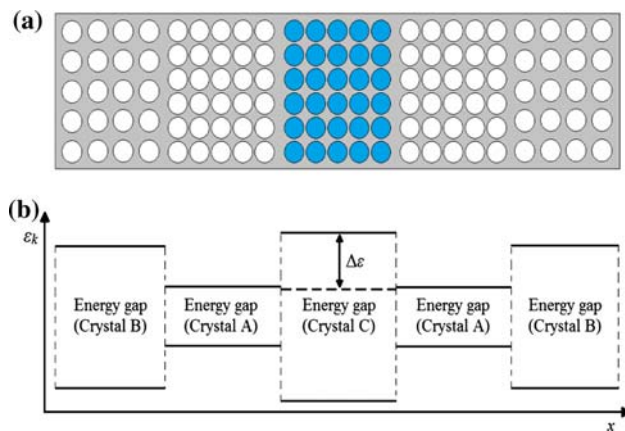


Fig. 1 Schematic diagram of the coupled heterostructure photonic crystal waveguide. **a** Cross-sectional view of the waveguide, depicting the photonic crystal arrangement within. The circles represent the spheres imbedded in each crystal, which are filled with air in photonic crystals A and B and a nonlinear dielectric material in photonic crystal C. The backbone material of each crystal consists of the same linear dielectric material. **b** Energy band structure of the waveguide in the direction of photon confinement. The dashed line located in the central photonic barrier illustrates how the position of the upper band edge of photonic crystal C shifts when the pump field is applied, where $\Delta\epsilon$ denotes the change in energy. Note that the lower band edge of crystal C also shifts in a similar manner upon the application of the pump field; this is not depicted here, since we are only concerned with the PQWs formed by the upper band edges of photonic crystals A, B and C

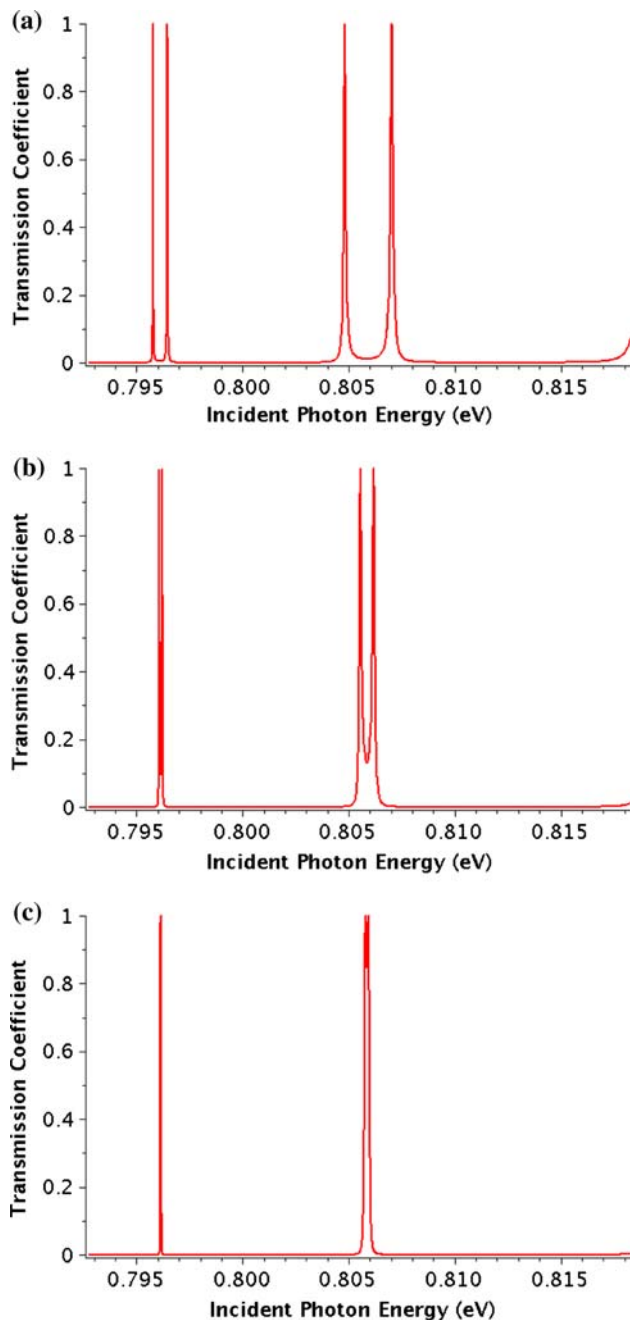


Fig. 2 Transmission spectra for the heterostructure waveguide in the direction of photon confinement, where the central barrier width is varied to observe its effect on the coupling between the waveguides. For all three plots, the outer photonic barriers were taken as $d_B = 5L_B$ and the widths of the wells were $d_A = 15L_A$. Here, the effect of the pump field was not considered. The barrier widths were varied as $d_C = 5L_C$ (a), $d_C = 10L_C$ (b) and $d_C = 15L_C$ (c). When the waveguides are close together, strong coupling of degenerate states enhances the energy-splitting effect. As the waveguides are separated, the interaction between degenerate states diminishes, and the energy splitting cannot be resolved

photonic barrier (crystal C) while leaving the pump field off. Here, we observe that when the waveguides are near one another, there is a strong spectral splitting effect, and

resonant peaks occur in pairs. However, as the waveguides are brought further away from one another, we find that the spectral splitting is diminished, eventually to the point where it can no longer be resolved. The spectral splitting effect observed here occurs due to a coupling between degenerate states of the two waveguides. Because the separation between waveguides is finite, there is some limited interaction between the electric fields of degenerate states. This interaction causes the degenerate states of the system to split into symmetric and anti-symmetric pairs, analogous to molecular bonding and anti-bonding pairs [26]. Thus in Fig. 2, each pair of resonant peaks corresponds to a degenerate state shared by the two waveguides, and for each pair, the lower-energy peak corresponds to the symmetric state, while the higher-energy peak is the anti-symmetric state. For degenerate states with higher energy, we observe that a proportionately stronger degree of spectral splitting occurs, which is due to enhanced photonic barrier penetration (and thus stronger coupling) at these energies. Thus, by changing the waveguide separation, the strength of the coupling between degenerate states can be varied, and the system can be switched between single and double bound states. From Fig. 2, we also note that for all resonant peaks, there is an associated degree of spectral broadening that increases with photon energy. This is attributed an enhanced tunneling rate for photons with energies nearer to the upper band edges of the photonic barriers [23].

The Kerr nonlinearity of photonic crystal C is investigated in Fig. 3, where numerical simulations of the energy band structure have been performed while varying the

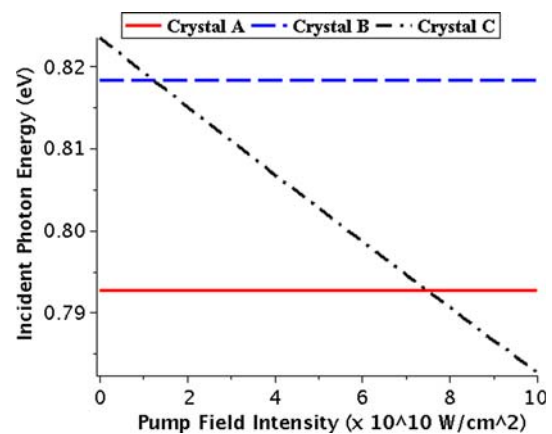


Fig. 3 Energy of the upper photonic band edge of photonic crystals A, B and C as the intensity of the pump field is varied. Since crystals A and B are essentially linear for this range of pump field intensity, their upper band edges are unaffected by the pump field. We see here that by applying a pump field with intensity around $8 \times 10^{10} \text{ W/cm}^2$, the upper band edge of crystal C can be shifted to just slightly below that of crystal A, effectively removing the photonic barrier separating the two waveguides in the heterostructure

intensity of an applied external pump field. Here, we only consider a range of pump field intensities up to 10^{11} W/cm², which effectively adds a small contribution to the index of refraction for the polystyrene spheres in photonic crystal C, as described by Eq. (2). Note that these pump fields are sufficiently small so that their effect on the index of refraction of titania is negligible, and so photonic crystals A and B are linear. In Fig. 3, the energies of the upper photonic band edges of photonic crystals A, B and C are shown. Bound photonic states within the waveguide heterostructure have energies between the upper band edges of crystals A and B. From Fig. 3, we see that by applying a sufficiently intense pump field to the structure, the upper band edge of photonic crystal C can be shifted to a level slightly below that of crystal A, which effectively removes the central photonic barrier separating the two waveguides. Essentially, this means that the system can be switched between a double waveguide and a single, wider waveguide by applying the pump field.

In Fig. 4, we consider transmission spectra of the coupled waveguide heterostructure for cases where the external pump field is on or off (i.e. applied or not). Here, we have considered a pump field with an intensity of 8×10^{10} W/cm², which lowers the energy of the upper band edge of photonic crystal C to 0.79064 eV. This is only slightly below the upper band edge of crystal A (0.79273 eV) and causes photonic crystal C to function as a photonic well rather than a barrier. In Fig. 4, we see that the transmission spectrum has changed dramatically by applying the pump field, where there is a greater number of resonant peaks that no longer occur in split pairs. By applying the pump field, the system has switched from a coupled waveguide structure to that of a single, wider waveguide consisting of the two photonic crystals A and the central layer of photonic crystal C. Since the number of bound photonic states depends on the width of the waveguide [23], we see a greater number of resonant peaks in the transmission spectrum. Thus, we have shown here that by applying a pump field, the system can be switched between single and double waveguide states (Fig. 4).

Conclusions

Here, we have considered coupled heterostructure photonic crystal waveguides made from two photonic crystals A and B and another nonlinear photonic crystal C, where the heterostructure is denoted as B/A/C/A/B. Due to the band structure engineering, light is confined within photonic crystal A by crystals B and C, causing two waveguides to form in crystal A. Using the transfer matrix method, we have studied the resonant photonic states within the

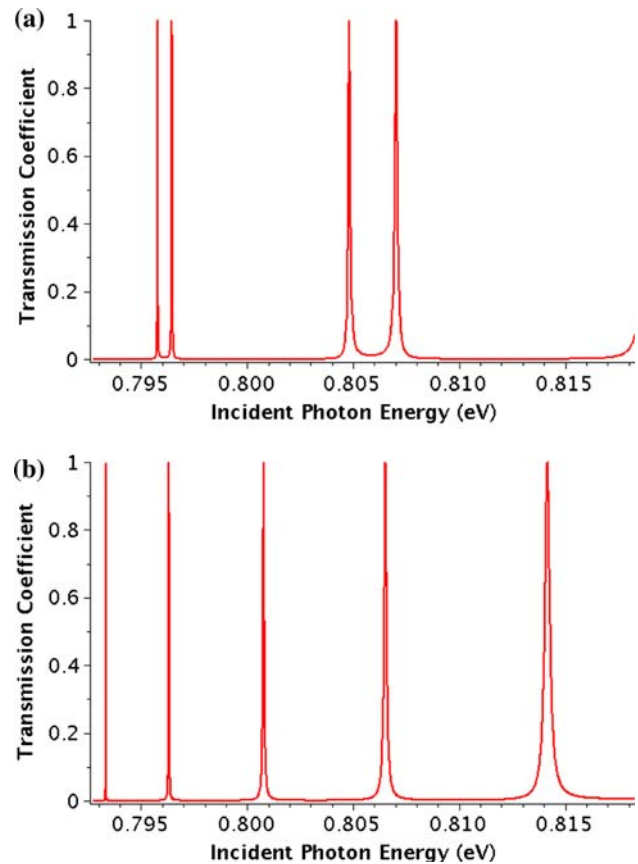


Fig. 4 Transmission spectra for the heterostructure waveguide in the direction of photon confinement, where the pump field is off (a) and on (b). For these plots, the outer photonic barriers were taken as $d_B = 5L_B$, the widths of the wells were $d_A = 15L_A$, and the central (nonlinear) barrier was taken as $d_C = 5L_C$. By applying the pump field, the system is switched between a double waveguide and a single, wider waveguide. This effectively switches the energy-splitting effect “off” or “on”

waveguides by calculating the transmission coefficient of the system in the direction of photon confinement. We have found that the number of bound photonic states within the waveguides can be controlled by varying the width and/or well depth of photonic crystal A. It was also found that when the waveguides are far away from each other, the energies of the bound photons are degenerate. However, by bringing the waveguides near one another, the degeneracy of the bound states is removed due to coupling between them, causing these states to undergo a twofold energy-splitting effect. Here, we have also investigated the non-linearity of photonic crystal C. By applying a pump laser, the photonic band gap of crystal C changes due to the Kerr nonlinearity. The change in band structure causes the central photonic barrier to disappear, switching the system between single and double waveguide states. Essentially, this means that the energy-splitting effect can be turned off by applying a pump laser. It is expected that these results

can be applied to develop new types of nanophotonic switching devices.

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